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Liquefied natural gas ship route planning: A risk analysis approach

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Abstract

We present a risk analysis approach for selecting alternate routes between liquefaction and re-gasification terminals. Due to lack of data related to incidents directly affecting LNG vessels as a result of the impressive historical safety records of the LNG industry, some parameters required for our risk analysis are estimated from a closely related hazmat cargo, Crude Oil. Our formulation is then used to solve a problem instance, using real-life data. Our results suggest: i) Depending on managerial preference, an alternate route with shorter distance may not necessarily be the vessel route of choice; ii) Risk analysis approach provides an insight into selection of a voyage route, taking into consideration activities (terrorism, or pirate attacks, or otherwise) that have been historically associated with alternate LNG vessel routes.

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Keywords: LNG vessel scheduling; Risk-based modeling; Incidents

1. Introduction

The global Liquefied Natural Gas (LNG) trade is expected to grow due to readily available supplies of gas worldwide and the renewed enforcement of a global climate regime [1]. More recently, the success of the oil and gas industry in terms of technological advances, especially with the advent of efficient fracking techniques have made it easier to access oil and gas deposits in hitherto difficult formations such as shale rocks.

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Apart from the identification of the improvement of existing technology in the storage, production and distribution of LNG as essential requirements for the continued success of the industry, the industry's existing safety performance, especially in handling and transportation between regional markets are key factors contributing to the growth of global LNG trade that need to be sustained. As most of the confirmed gas reserves are located far away from their demand markets and usually between continents, it is apparent that maritime transportation will continue to play a pivotal role in the LNG trade.

2. Problem statement

Since LNG often has to be transported over long distances across maritime infrastructures to their final destinations, safety along these sea routes is of paramount importance. Although historical records strongly indicate the involvement of LNG carriers in accidents to be negligible in comparison to other types of vessels [2], the consequent economic and catastrophic losses that may occur when a single vessel is involved in an accident needs to be accorded great attention. In this paper, we apply a risk-based methodology to the LNG routing problem presented in [3].

In Risk parlance, risk is taken as the expected consequence of incidents. Calculation of expected consequence is conditioned on the types of possible incidents [4]:

$$E\left(C\right)=\sum_{j}E\left(C\mid I_{j}\right)p(I_{j}) \tag{1}$$

The two components of equation (1) respectively refer to the expected consequence given the occurrence of an incident j, and the probability that an incident of type j occurs. However, a successful intrusion (attack) may or may not lead to an incident. Hence, equation (1) can be written as ([4], [5], etc.):

$$\mathrm{E}\left(\mathrm{C}\right)=\sum_{j}\left[E\left(C|I_{j}\right)*\left\{\sum_{k}p\left(I_{j}|A_{k}\right)p\left(A_{k}\right)\right\}\right] \tag{2}$$

The newly introduced conditional probability in equation (2) is the probability of a successful attack/intrusion given that the attack has already occurred and the last term is the probability of the occurrence of the attack k.

In sequence, the probabilities in equation (2) are respectively referred to as Expected consequence of an incident C, Vulnerability of targeted assets/infrastructure V, and Probability that an attack (activity) occurs T in the quantification of risk ([4],[5], [6], [7], etc.).

3. Methodology- Risk-based LNG routing

In order not to disrupt the flow of presentation in this paper, the details of our modified risk-based formulation of [3]'s model are presented in the appendix.

In our methodology, LNG spillage is identified as a consequence due to the following compelling reasons:

- Compared to other indices such as ship damage and fatality (related to human lives), spillage can be easily quantified and its economic effects can be readily computed with widely available data.
- LNG spillage through the compromise of vessel cargo containment can be attributed to other vessel accident scenarios such as collision, grounding and Contacts. In fact, [2] identifies the culpability of these three generic scenarios in about 90% of total risk related to LNG carriers.

Since risk information for rare events inherently suffers from sparseness of accident data, expert judgment is often used in developing frequency data for risk analysis ([8], [9], etc.). However, experts' biases and individual experiences may affect the integrity of information recommended. Moreover, the information at their disposal will usually be solely based on their past experiences and may be inadequate in predicting the occurrence of future incidents. In the alternative, we propose the use and integration of data available from the transport of a closely related cargo vessel (Oil Tanker vessels) in our methodology.

In recognition of the past reliance on LNG imports by the US economy as well the future expansion of US LNG exports, the US Department of Energy (DOE) has funded several studies related to the large scale spillage of LNG. As a part of these studies, spillage as a result of accidental or intentional breach of LNG cargo tanks has been studied in [10]. Parameters required as inputs in our methodology can be readily obtained from this study.

3.1. Risk estimation model and assessment

In accordance with the terminologies adopted in the Risk literature and our specific problem, the first two conditional probabilities in equation (2) are *'the expected consequence given the occurrence of a spill incident j'* and *'conditional probability of a spill occurrence given that the breach (in the LNG cargo containment system) has already occurred*' respectively, and the last term is *'the probability of a breach(in the LNG cargo containment system) occurrence'*.

Risk on a route rt can be computed thus:

$$R_{rt} = \sum_{w \in W} C_{rt}^{w} V_{rt}^{w} T_{rt}^{w} \tag{3}$$

It should be noted that since neither of the risk component in equation (2) is strictly a function of the same index (j and k in equation 2), an index w of set W is introduced to indicate this. In reality, the risk components on a route are not homogenous. Therefore, we use segments to represent route subdivisions where a route is made of segments/portions/zones l, l+1,……,q. Hence, risk on a segment l is:

$$R_{rt,l} = \sum_{w \in W} C_{rt,l}^{w} V_{rt,l}^{w} T_{rt,l}^{w} \tag{4}$$

For ease of notation, we drop subscript rt and the expected consequence for segment l+1 ([11]) is:

$$\sum_{w2 \in W2} \left(\left\{ 1 - T_{l}^{w2} \right\} * \sum_{w \in W} C_{l+1}^{w} V_{l+1}^{w} T_{l+1}^{w} \right) \tag{5}$$

where set W2 represents the set of activities (breaches) that do not result into LNG spillage.

Likewise, the expected consequence on segment l+2 is:

$$\sum_{w2 \in W2} \left(\left\{ 1 - T_{l+1}^{w2} \right\} * \sum_{w \in W} C_{l+2}^{w} V_{l+2}^{w} T_{l+2}^{w} \right) \tag{6}$$

Hence, total Expected consequence on route rt with a total number of q segments is then:

$$Risk_{link\,1} + \sum_{k \in K \setminus \{k \neq 1\}} \left(\sum_{w2 \in W2} \left\{ Risk_{link\,k} \prod_{j \in K \setminus \{j>1, j \le k\}} \left[1 - T_{j-1}^{w2} \right] \right\} \right) \tag{7}$$

$$= \quad Risk_{link\,1} + \sum_{k=2}^{q} \left(\sum_{w2 \in W2} \left\{ Risk_{link\,k} \prod_{j=2}^{k} \left[1 - T_{j-1}^{w2} \right] \right\} \right) \tag{8}$$

Based on studies in [10], spill events considered are: '*Small/No spill m', 'Medium spills M', and 'Large spills L'*. Since the consequence of low breach size typically falls within current spill detection and safety systems on Moss and Membrane LNG ships ([10]), we reasonably assume an LNG vessel continues to travel except when a medium or large breach occurs (implying the occurrence of a small breach doesn't terminate the voyage).

Therefore, spill risk on route rt,

$$Risk_{route,rt} = C^M V^M T^M + C^L V^L T^L \tag{9}$$

And spill risk on a segment l is

$$Risk_{route\ rt,segment\ l} = C^M_{rt,l} V^M_{rt,l} T^M_{rt,l} + C^L_{rt,l} V^L_{rt,l} T^L_{rt,l} \tag{10}$$

Expected consequence for segment l+1 is:

$$\begin{aligned} Risk_{route\ rt,segment\ l+1} &= (1-T_l^L)\,(C^M_{l+1}V^M_{l+1}T^M_{l+1} + C^L_{l+1}V^L_{l+1}T^L_{l+1}) \\ &+ (1-T_l^M)\,(C^M_{l+1}V^M_{l+1}T^M_{l+1} + C^L_{l+1}V^L_{l+1}T^L_{l+1}) \qquad (11) \\ &= (2-T_l^L - T_l^M)\,(C^M_{l+1}V^M_{l+1}T^M_{l+1} + C^L_{l+1}V^L_{l+1}T^L_{l+1}) \qquad (12) \end{aligned}$$

Likewise, expected consequence for segment l+2 is:

$$Risk_{route\ rt,segment\ l+2} = (2-T_l^L - T_l^M)\,(C^M_{l+1}V^M_{l+1}T^M_{l+1} + C^L_{l+1}V^L_{l+1}T^L_{l+1}) \tag{13}$$

And total Expected consequence on route rt with a total number of q segments is then:

$$Risk_{route\ rt} = Risk_{segment\ 1} + \sum_{k=2}^{q}\left(Risk_{segment\ k} \prod_{j=2}^{k}\left(2 - T^L_{j-1} - T^M_{j-1}\right)\right) \tag{14}$$

3.2. Expected consequence of a spill event

Apart from loss of cargo, the incident of LNG spillage can lead to pool fires, damage to vessel steel structures (as a result of cryogenic LNG flow and high temperature due to extensive fires), large fires, human casualty, etc. ([10]). While all these are identified as possible consequences of LNG spillage, only the loss of cargo consequence can be readily ascertained without extensive use of complex estimation models or large scale expensive experimental procedures. Using the loss of cargo criterion, all that is needed is the volume of cargo as well as its current market price (or price hitherto agreed to in the contractual agreements). Hence, for our purpose, we consider the expected consequence of LNG spillage as the cost per billion cubic meters bcm cost of cargo spill (to include cargo loss, contract penalty –if any, regulatory environmental fee–if any, etc.).

It should be noted that different quantitative models have been developed for the cost involved in cleaning crude oil spills (e.g. in [12], [13], etc.). However, unlike Oil spills, there is no need for environmental clean-up of LNG spills because the liquid will quickly evaporate, thus making the environmental cleaning of LNG spills unnecessary.

LNG Spill size volume as a function of breach volume extracted from experimental results presented in [10] is shown in Table 1.

Table 1. Spill size volume as a function of breach volume [10].

Spill Size	LNG Flow Rate Loss	Volume Rate Loss per time t
Small	0.001X >	< 0.001Xt
Medium	~ 0.167X	~ 0.167Xt
Large Spill	X	Xt

where X is the volume of LNG cargo

3.3. Vulnerability of LNG Vessel

The probability of a successful breach on a vessel (and by extension, its tanks) cannot be easily ascertained. The double-hull feature and other features on the vessel suggest minimal intrusion in the case of small collisions. However, a deliberate attack on vessel, a severe unexpected inclement weather, grounding or collision with very large vessels is expected to result into high probabilities of successful breaches.

For our purpose in this paper, we estimate the probability thus:

- Identify an acceptable division of alternate sea routes between origin ports and regasification terminal using division of world oceans (navigated by the LNG vessels) into 31 zones as done in [9]. In the alternative, the approach adopted in [11] where route sub-sections are determined by lines of longitude and latitudes will also suffice.
- Depending on the events under consideration, a database of events is obtained and its contents analyzed. The database (related to piracy attacks) we use is that made available in [14].
- For each segment in the route, a corresponding probability is computed based on a utility function; with the events having the highest frequency assigned a vulnerability of 1 or a probability close to 1.

3.4. LNG Spillage- Probability of breach occurrence

Ideally and in accordance with accepted risk methodologies, this probability should be obtained from historic safety data in LNG shipping and is usually computed as incident frequency per ship year (e.g. in [15])

Without access to such recent data, we use data presented in [2] and identify the *'failure of cargo containment system'* as a specific accident category related to LNG spillage. Amongst other reasons, the category is chosen from intuition. Moreover, the referenced paper clearly identified it as an incident that could have resulted from other categories such as grounding, collision and contacts. Thus, T_l^i from equations 7 - 14 can then be estimated thus:

$$T_l^i = \alpha_i * \textit{frequency per ship year} \quad \text{where } i \in (M, L) \tag{15}$$

$$= \alpha_i * 0.0095 \tag{16}$$

Again, due to lack of historic data on LNG spills, we make use of oil tanker spill statistics compiled by the International Tanker Owners Pollution Federation, ITOPF [17] to approximate α_i. While we acknowledge that the two spillages are fundamentally different, we rationalize that spill category based on volume of oil spillage as reported by ITOPF is similar to the LNG spill types we have adopted and the proportions of these categories in both spill situations are analogous because liquid natural gas handling is more like handling oil [16].

Table 2. Comparison: LNG Spill Types [10] versus ITOPF oil spill sizes [17].

LNG Spill types	Oil Spill Size equivalents (from ITOPF)
Small Spill	<7 tonnes (<50 bbls)
Medium Spill	7–700 tonnes (50–5,000 bbls)
Large Spill	700 tonnes (>5,000 bbls)

The ITOPF data includes the type of oil spilt, the spill amount, the cause and location of the incident and the vessel involved. Although the actual amount spilt is also recorded, the spill size categorized is as shown in Table 2. With about 10,000 incidents, the vast majority of all incidents (81%) fall under the smallest category i.e. <7 tonnes [17]. In the absence of specific LNG spill data for the failure of cargo containment system, we use available data on oil spills related to historical spillage from 1970-2013 and approximate α_i based on data presented in [17].

Hence $\alpha_M = {}^{1351}\!/_{10000} = 0.1351, \alpha_L = {}^{459}\!/_{10000} = 0.0459.$

4. Computational study- Case study results

We present results using a modification of the test case described in [3]. While the liquefaction plant is a country in the Middle East, required depots to be served are located in North America, Europe, and South America. Data presented in [3] such as the specification of LNG tankers, customer demands in each time periods and other parameters are maintained. Where applicable, data presented for the first three customer demands in the terminals are maintained to coincide with the three customers identified in this paper. However, distance (in Nautical miles Nm) and computed raw risk data (based on section 3) in this case study are shown in Table 3. In addition, uncertainties as a result of boil off gas BOG introduced in [3] are excluded in the implementation presented in this paper.

The model is implemented in GAMS and solved using CPLEX. All MIPs are solved within a relative tolerance of 3% duality gap, and all computational runs are made on a 3.00 GHz Intel Xeon machine with 400 GB of memory, running CPLEX version.

Table 3. Distance (and raw risk data) between depot and liquefaction terminals.

	Routes	Terminal 2	Terminal 3	Terminal 4
Depot	Route 1	9789 (0.000453)	5028 (0.000294)	8376 (0.000423)
	Route 2	12597 (0.000324)	10165 (0.000384)	9540 (0.000268)
Terminal 2	Route 1		4781(0.000048)	5663 (0.000050)
	Route 2		5259 (0.000095)	6229 (0.000019)
Terminal 3	Route 1			4512 (0.000108)
	Route 2			-

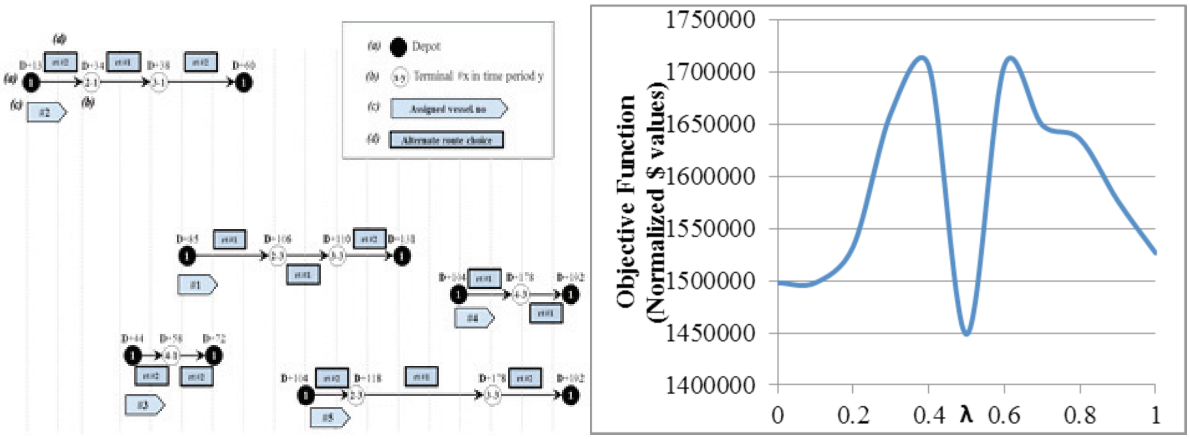

Fig. 1. (a) Sample Delivery Schedule; (b) Objective function versus decision maker's preference.

Results obtained for the case study is summarized below:

- Irrespective of decision maker preference, choice of route between 'the depot and terminal 3', 'terminal 2 and terminal 3', 'terminal 3 and terminal 4' are always the same, given that such a voyage is included in the optimal delivery plan. While only a single route option exists in the latter voyage, distance and risk considerations favor a particular alternate route in the former voyages.
- However for all other voyages (apart from those identified above), choice of the alternate routes is dependent on the decision maker's preference. Again, this is applicable if the particular voyage is included in the optimal delivery plan returned by the model. Figure 1(a) shows a sample optimized 6 month delivery schedule/routing plan from D+1 to D+192. See [3] for more clarification. In addition, alternate choice of voyage route is indicated.
- Figure 1(b) indicates that the appropriate choice of λ for the case study lies between 0.4 and 0.6. Neglecting either of the two terms in the objective function (see Appendix) doesn't give the least aggregated cost.

5. Conclusion

In this paper, we presented a framework for risk-based transportation of LNG vessels. Due to lack of data as a result of the current lofty safety records in the LNG transportation industry, some parameters were estimated from Crude oil, a similar petrochemical energy resource. Afterwards, we integrated the described risk methodology into the model described in [3] and used our methodology to solve a realistic sample case study.

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Appendix A. Mathematical model of Risk-based LNG Vehicle Routing Problem

A.1. Indices and sets, variables, parameters, objective functions and constraints

In addition to the indices included in [3], we add the index $rt \in RT$ defined thus

RT	Set of alternative routes from i to j
$rt \in RT$	Index of alternative routes

Hence, $x^1_{i,j,k}$ as defined in [3] is re-defined as

$x^1_{i,j,k,rt}$	*Binary variable to represent whether the arc from* $i, i \in V$ *to* $j, j \in V \setminus \{i\}$ *by vessel type* k *using route,* rt;

And all other variables remain as defined in the reference paper. In addition to parameters defined in [3], the following parameters are included:

$nDAY_{i,j,rt}$	(Normalized) Estimated travel distance (nautical miles) from i to j using route rt
$nRisk_{i,j,rt}$	(Normalized) Aggregated Risk consequence on alternative route, rt (give units)
λ	Decision maker preference (between 0 and 1)

The objective function (aggregated cost) is redefined thus:

$$\min \begin{array}{l} (1-\lambda)\sum_{rt\in RT}\sum_{(i,j)\in A}\sum_{k\in K}(nDAY_{i,j,rt} * DSC_k * x^1_{i,j,k,rt}) \\ +\lambda\sum_{rt\in RT}\sum_{(i,j)\in A}\sum_{k\in K}(nRisk_{i,j,rt} * DSC_k * x^1_{i,j,k,rt}) \end{array} \quad \text{(A1)}$$

All constraints presented in [3] still remain applicable, albeit with the new indexing and variable declarations taken into consideration. For example, equation (2) in the reference paper becomes:

$$\sum_{rt\in RT}\sum_{k\in K} x^1_{s,s+|S|(t-1),k,rt} = 0 \qquad \forall s\in S, t\in T\setminus\{1\} \quad \text{(A2)}$$

And equation (16) becomes:

$$y_{i,j} \geq \alpha VC_r x^1_{i,j,r,rt} \qquad \forall (i,j)\in A, r\subseteq K, rt\in RT\ , \quad \text{(A3)}$$

In addition, the following constraints become applicable:

$$\sum_{rt\in RT} x^1_{i,j,k,rt} = 1 \qquad \forall (i,j)\in A, k\in K \quad \text{(A4)}$$

The additional constraint, A4 ensures only a single route is chosen for any voyage.

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